

**BEHAVIOR OF FRP  
COMPOSITE-STRENGTHENED  
BEAMS UNDER STATIC AND  
CYCLIC LOADING**

**Summary Report**

**SPR 387.011**

# **BEHAVIOR OF FRP COMPOSITE-STRENGTHENED BEAMS UNDER STATIC AND CYCLIC LOADING**

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by

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| 16. Abstract<br><br>Small, concrete beams with no steel reinforcement were externally strengthened with eight different configurations of fiber reinforced polymer composites. The reinforcement configurations consisted of high and low modulus epoxy, high and low modulus fiber, and 1 and 2 composite layers. Load capacity tests were conducted for all eight configurations, and fatigue tests were conducted for two of the configurations. Beams with the higher modulus epoxy had more load capacity than beams with the lower modulus epoxy. However, this enhancement decreased as the failure mode changed from flexural failure to less desirable failure modes. The modulus of the resin had no effect on beam stiffness. The fatigue strength of the beams was strongly dependent on the load capacity of the beams; consequently, higher modulus epoxy could improve the fatigue performance of concrete beams. |  |                             |  |   |           |
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# SI\* (MODERN METRIC) CONVERSION FACTORS

| APPROXIMATE CONVERSIONS TO SI UNITS |                        |             |                     | APPROXIMATE CONVERSIONS FROM SI UNITS |                     |             |                      |
|-------------------------------------|------------------------|-------------|---------------------|---------------------------------------|---------------------|-------------|----------------------|
| Symbol                              | When You Know          | Multiply By | To Find             | Symbol                                | When You Know       | Multiply By | To Find              |
| <u>LENGTH</u>                       |                        |             |                     | <u>LENGTH</u>                         |                     |             |                      |
| in                                  | inches                 | 25.4        | millimeters         | mm                                    | millimeters         | 0.039       | inches               |
| ft                                  | feet                   | 0.305       | meters              | m                                     | meters              | 3.28        | feet                 |
| yd                                  | yards                  | 0.914       | meters              | m                                     | meters              | 1.09        | yards                |
| mi                                  | miles                  | 1.61        | kilometers          | km                                    | kilometers          | 0.621       | miles                |
| <u>AREA</u>                         |                        |             |                     | <u>AREA</u>                           |                     |             |                      |
| in <sup>2</sup>                     | square inches          | 645.2       | millimeters squared | mm <sup>2</sup>                       | millimeters squared | 0.0016      | square inches        |
| ft <sup>2</sup>                     | square feet            | 0.093       | meters squared      | m <sup>2</sup>                        | meters squared      | 10.764      | square feet          |
| yd <sup>2</sup>                     | square yards           | 0.836       | meters squared      | m <sup>2</sup>                        | hectares            | 2.47        | acres                |
| ac                                  | acres                  | 0.405       | hectares            | ha                                    | kilometers squared  | 0.386       | square miles         |
| mi <sup>2</sup>                     | square miles           | 2.59        | kilometers squared  | km <sup>2</sup>                       | <u>VOLUME</u>       |             |                      |
| <u>VOLUME</u>                       |                        |             |                     | <u>VOLUME</u>                         |                     |             |                      |
| fl oz                               | fluid ounces           | 29.57       | milliliters         | mL                                    | milliliters         | 0.034       | fluid ounces         |
| gal                                 | gallons                | 3.785       | liters              | L                                     | liters              | 0.264       | gallons              |
| ft <sup>3</sup>                     | cubic feet             | 0.028       | meters cubed        | m <sup>3</sup>                        | meters cubed        | 35.315      | cubic feet           |
| yd <sup>3</sup>                     | cubic yards            | 0.765       | meters cubed        | m <sup>3</sup>                        | meters cubed        | 1.308       | cubic yards          |
| <u>MASS</u>                         |                        |             |                     | <u>MASS</u>                           |                     |             |                      |
| oz                                  | ounces                 | 28.35       | grams               | g                                     | grams               | 0.035       | ounces               |
| lb                                  | pounds                 | 0.454       | kilograms           | kg                                    | kilograms           | 2.205       | pounds               |
| T                                   | short tons (2000 lb)   | 0.907       | megagrams           | Mg                                    | megagrams           | 1.102       | short tons (2000 lb) |
| <u>TEMPERATURE (exact)</u>          |                        |             |                     | <u>TEMPERATURE (exact)</u>            |                     |             |                      |
| °F                                  | Fahrenheit temperature | 5(F-32)/9   | Celsius temperature | °C                                    | Celsius temperature | 1.8C + 32   | Fahrenheit           |

°F

-40

0

32

40

80

98.6

120

160

200

212

°C

-40

-20

0

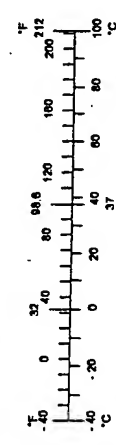
20

40

60

80

100



NOTE: Volumes greater than 1000 L shall be shown in m<sup>3</sup>.

\* SI is the symbol for the International System of Measurement (4-7-94 jbp)

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# BEHAVIOR OF FRP COMPOSITE-STRENGTHENED BEAMS UNDER STATIC AND CYCLIC LOADING

## TABLE OF CONTENTS

|  |    |
|--|----|
| 1.0 INTRODUCTION.....                    | 1  |
| 2.0 METHOD.....                          | 3  |
| 2.1 STATIC LOAD TESTING.....             | 3  |
| 2.2 FATIGUE TESTING.....                 | 4  |
| 3.0 RESULTS AND DISCUSSION .....         | 5  |
| 3.1 LOAD TESTS.....                      | 5  |
| 3.2 FATIGUE TESTS.....                   | 6  |
| 4.0 CONCLUSIONS AND RECOMMENDATIONS..... | 9  |
| 5.0 REFERENCES.....                      | 11 |

## LIST OF TABLES

|  |   |
|--|---|
| Table 2.1: Composite configurations for static load tests..... | 3 |
| Table 2.2: Composite configurations for fatigue tests.....     | 4 |
| Table 3.1: Results of load tests.....                          | 5 |
| Table 3.2: Failure modes .....                                 | 6 |
| Table 3.3: Fatigue test results .....                          | 7 |

## LIST OF FIGURES

|   |   |
|---|---|
| Figure 2.1: Test configuration.....                     | 4 |
| Figure 3.1: Load amplitude versus number of cycles..... | 7 |
| Figure 3.2: Load ratio versus number of cycles .....    | 8 |

## 1.0 INTRODUCTION

Externally applied fiber reinforced polymer (FRP) composites applied as a wet lay-up are increasingly being used to strengthen, repair, and rehabilitate civil structures. Performance of a structure with composites depends on the structural design and the orientation, properties, and proportion of the constituents (fibers and polymer resin). In the case of a wet lay-up, the matrix resin is also the resin that bonds the composite laminate to the structure. The resin is critical for effectively transferring strain to the composite over the life of the structure. Design engineers can choose from many composite systems with a wide range of resin properties. It is unclear, however, whether there are resin and fiber combinations that perform better than others.

A study conducted by Oregon State University and funded by Oregon Department of Transportation investigated the effects of different epoxy resin and fiber combinations on the static and cyclic behavior of small, concrete beams strengthened with FRP composites. The results of that study are reported in a masters project report from the Department of Civil, Construction, and Environmental Engineering at Oregon State University (*Seamanontaprinya, 2001*). This report is a summary of that thesis.

## 2.0 METHOD

### 2.1 STATIC LOAD TESTING

Thirty-eight unreinforced concrete beams were cast with dimensions 150 mm x 150 mm x 530 mm, using concrete with a nominal 28-day strength of 32 MPa. Twenty-four beams were reinforced with eight composite strengthening configurations using high and low modulus epoxy, high and low modulus fiber, and 1 and 2 composite layers, as shown in Table 2.1.

Table 2.1: Composite configurations for static load tests

| Identification | Composite Configuration              | Number of FRP Layers | Number of Specimens |
|----------------|--------------------------------------|----------------------|---------------------|
| CONT           | Unreinforced concrete beam           | 0                    | 3                   |
| 1LG            | Low-modulus resin with glass fiber   | 1                    | 3                   |
| 2LG            | Low-modulus resin with glass fiber   | 2                    | 3                   |
| 1LC            | Low-modulus resin with carbon fiber  | 1                    | 3                   |
| 2LC            | Low-modulus resin with carbon fiber  | 2                    | 3                   |
| 1HG            | High-modulus resin with glass fiber  | 1                    | 3                   |
| 2HG            | High-modulus resin with glass fiber  | 2                    | 3                   |
| 1HC            | High-modulus resin with carbon fiber | 1                    | 3                   |
| 2HC            | High-modulus resin with carbon fiber | 2                    | 3                   |
|                |                                      |                      | Total: 27           |

Mitsubishi Epotherm® L700S resin was used for the low modulus epoxy, and Tyfo® S resin was used for the high modulus epoxy. Glass fiber from the Fyfe Corporation – Tyfo® SHE-51 – was used as the low modulus fiber; and carbon fiber from the Fyfe Corporation – Tyfo®SCH-41 – was used as the high modulus fiber.

These beams, along with three unstrengthened control beams, were loaded to failure in third-point loading in accordance with ASTM C78, as shown in Figure 2.1 (ASTM 2001).



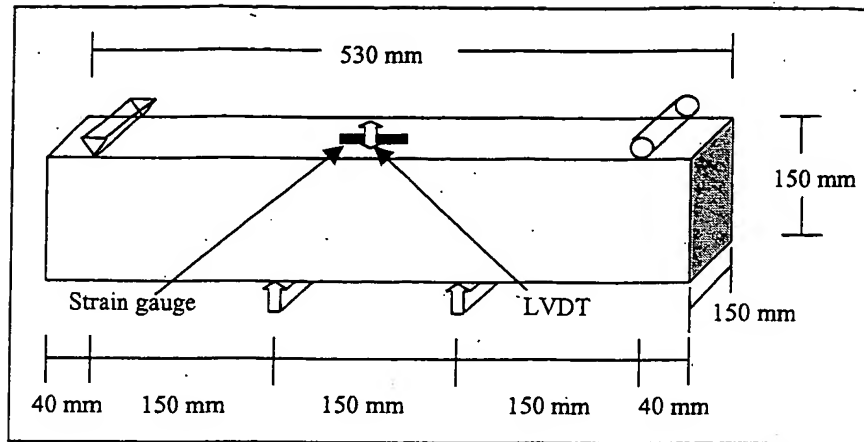


Figure 2.1: Test configuration

## 2.2 FATIGUE TESTING

The remaining 10 beams were reinforced with two composite strengthening configurations, as shown in Table 2.2.

Table 2.2: Composite configurations for fatigue tests

| Identification | Composite Configuration              | Number of FRP Layers | Number of Specimens |
|----------------|--------------------------------------|----------------------|---------------------|
| CONT           | Unreinforced concrete beam           | 0                    | 1                   |
| 1LG            | Low-modulus resin with glass fiber   | 1                    | 5                   |
| 2HC            | High-modulus resin with carbon fiber | 2                    | 5                   |
|                |                                      |                      | Total: 11           |

These beams, along with one unstrengthened control beam, were fatigue tested at 0.5 Hz under the third-point loading shown in Figure 2.1. The minimum load for each test was maintained at 0.67 kN (150 lb). The 1LG configuration was the low stiffness and strength condition, while the 2HC configuration was the high stiffness and strength condition of the eight composite combinations.

### 3.0 RESULTS AND DISCUSSION

#### 3.1 LOAD TESTS

The results of the load tests are summarized in Table 3.1, and the failure modes of the tests are described in Table 3.2.

**Table 3.1: Results of load tests**

| Configuration | Load (kN)  | Deflection (mm) | Strain (microstrain) | Post-Crack Stiffness (kN/mm) | Failure Mode  |
|---------------|------------|-----------------|----------------------|------------------------------|---|
| CONT          | 27         | 0.04            | 230                  |                              | Flexure   |
|               | 29         | 0.05            | 200                  |                              |   |
|               | 30         | NA              | 190                  |                              |   |
|               | Mean = 29  | Mean = 0.03     | Mean = 210           | 0                            |   |
| 1LG           | 97         | 3.23            | 12500                | 20                           | Flexure with FRP rupture                                    |
|               | 98         | 3.27            | 11900                | 19                           |   |
|               | 127        | 4.43            | 15500                | 20                           |   |
|               | Mean = 107 | Mean = 3.64     | Mean = 13300         | Mean = 20                    |   |
| 2LG           | 142        | 2.99            | 10200                | 36                           | Shear and flexure   |
|               | 189        | 3.79            | 13300                | 41                           |   |
|               | 195        | 3.78            | 14900                | 42                           |   |
|               | Mean = 175 | Mean = 3.52     | Mean = 12800         | Mean = 39                    |   |
| 1LC           | 141        | 2.28            | 7800                 | 47                           | Shear and flexure   |
|               | 149        | 3.17            | 8600                 | 35                           |   |
|               | 158        | 3.09            | 9000                 | 38                           |   |
|               | Mean = 149 | Mean = 2.85     | Mean = 8500          | Mean = 40                    |   |
| 2LC           | 179        | 1.97            | 5400                 | 74                           | Shear   |
|               | 199        | 1.86            | 5400                 | 88                           |   |
|               | 210        | 2.48            | 6100                 | 67                           |   |
|               | Mean = 196 | Mean = 2.10     | Mean = 5600          | Mean = 77                    |   |
| 1HG           | 134        | 4.23            | 16400                | 23                           | Flexure with internal shear failure of laminate             |
|               | 136        | 4.70            | 16300                | 20                           |   |
|               | 143        | 5.29            | 17100                | 18                           |   |
|               | Mean = 138 | Mean = 4.74     | Mean = 16600         | Mean = 20                    |   |
| 2HG           | 196        | 3.96            | 12600                | 42                           | Shear and flexure. 2 failed with concrete crushing          |
|               | 203        | 4.69            | 14600                | 35                           |   |
|               | 220        | 4.13            | 14600                | 42                           |   |
|               | Mean = 206 | Mean = 4.26     | Mean = 13900         | Mean = 40                    |   |
| 1HC           | 159        | 3.38            | 9600                 | 38                           | Shear and flexure. 2 had internal shear failure of laminate |
|               | 171        | 3.46            | 11600                | 38                           |   |
|               | 174        | 3.13            | 9300                 | 42                           |   |
|               | Mean = 168 | Mean = 3.32     | Mean = 10200         | Mean = 39                    |   |
| 2HC           | 196        | 1.87            | 5200                 | 83                           | Shear   |
|               | 201        | 2.07            | 5400                 | 76                           |   |
|               | 223        | 2.17            | 6300                 | 82                           |   |
|               | Mean = 206 | Mean = 2.04     | Mean = 5600          | Mean = 80                    |   |

**Table 3.2: Failure modes**

| Failure Mode                       | Description   |
|------------------------------------|---|
| Flexure                            | Flexure crack develops from tensile side in the center of specimen between loading points and propagates to compression side. |
| Shear                              | Shear crack develops on the tensile side of specimen near support and propagates about 45° angle to the loading point.        |
| Shear and flexure                  | Shear crack propagates to the center of specimen, shifts to flexure, and continues to propagate to the compression side.      |
| Internal shear failure of laminate | Shear stress in the resin exceeds its capacity  |
| Concrete crushing                  | Flexural cracking with concrete crushing on compression side.   |

As expected, beams with 2 layers of a particular fiber type had higher load capacity and stiffness than beams with 1 layer. Also, carbon fiber produced higher capacity and stiffness in the beams than the glass fiber. The resin had no effect on the stiffness; however, the high-modulus resin increased the load capacity up to 29%. A smaller increase in load capacity – as low as 5% – was observed when the failure mode switched from a desirable flexure failure to shear failure modes in beams strengthened with the higher stiffness composite configurations. This result indicated that for properly designed beams, the resin could appreciably affect the load capacity of the beam.

### 3.2 FATIGUE TESTS

The fatigue test results are shown in Table 3.3. Load ratios were calculated using the following equation:

$$R_l = \frac{L}{L_{ult}} \quad (3-1)$$

where

$R_l$  = load ratio,

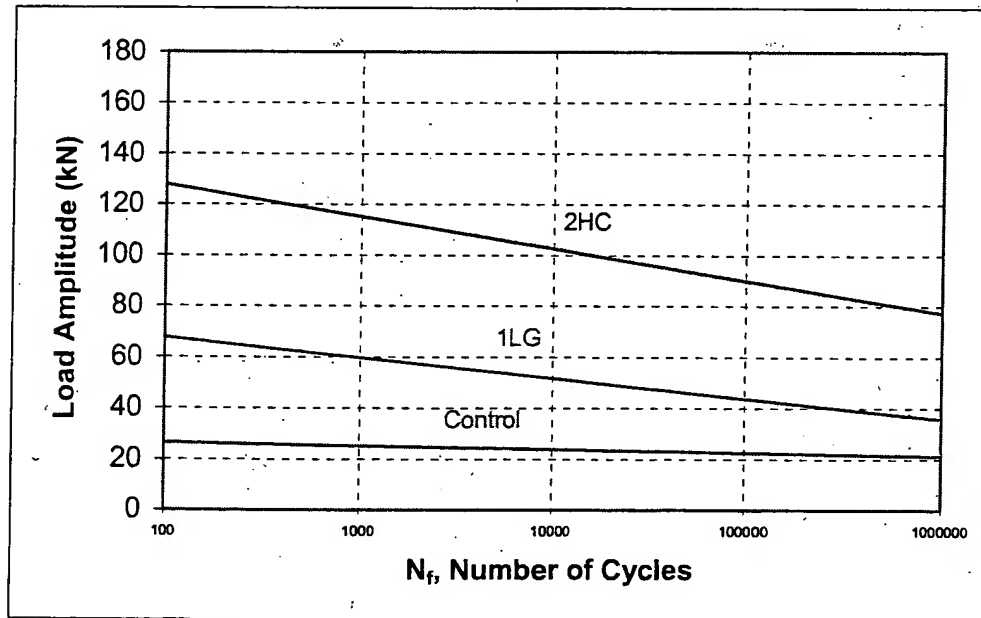
$L$  = applied load, and

$L_{ult}$  = static ultimate loading capacity

**Table 3.3: Fatigue test results**

| Configuration | Load Amplitude (kN) | Load Ratio | Number of Cycles | Failure Mode      |
|---------------|---------------------|------------|------------------|-------------------|
| CONT          | 29.0                | 1.000      | 1                | Flexure           |
|               | 22.2                | 0.766      | 136000           |                   |
| 1LG           | 107.0               | 1.000      | -                | Flexure           |
|               | 72.8                | 0.680      | 80               |                   |
|               | 64.3                | 0.601      | 180              |                   |
|               | 55.5                | 0.519      | 1200             |                   |
|               | 44.6                | 0.417      | 36000            |                   |
|               | 40.0                | 0.374      | 648000           |                   |
| 2HC           | 206.0               | 1.000      | -                | Shear and Flexure |
|               | 105.0               | 0.510      | 11700            |                   |
|               | 104.9               | 0.509      | 13700            |                   |
|               | 89.1                | 0.433      | 32400            |                   |
|               | 86.4                | 0.419      | 99800            |                   |
|               | 81.0                | 0.393      | 916400           |                   |

Figure 3.1 shows that the higher strength and stiffness composite configuration, 2HC, provided better fatigue response. Figure 3.2 indicates that the fatigue strength of the composite-strengthened beams is strongly dependent on the capacity of the beams. Equations were established to predict fatigue life for the beams used in this study.



**Figure 3.1: Load amplitude versus number of cycles**

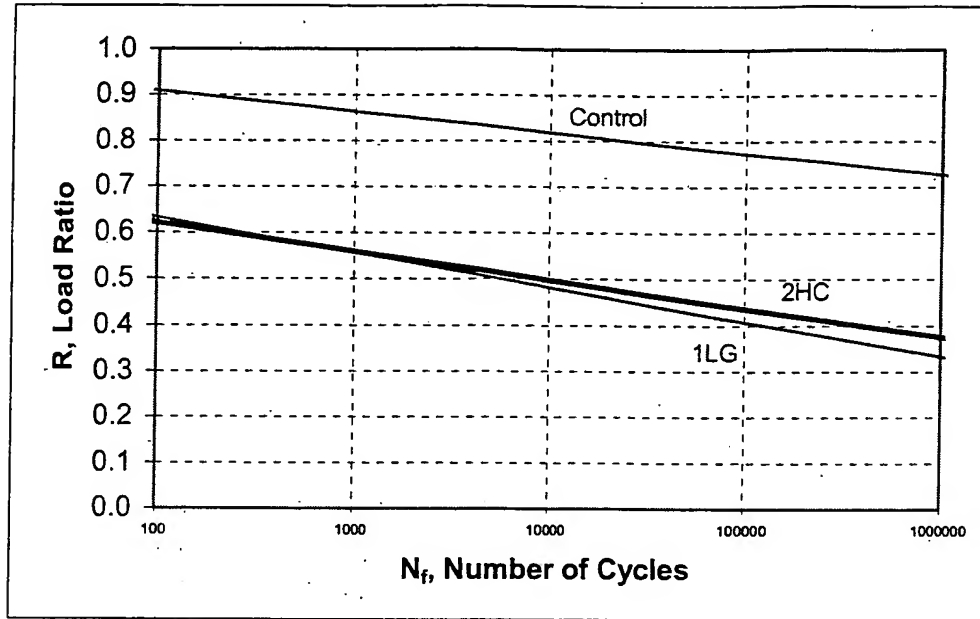


Figure 3.2: Load ratio versus number of cycles

## 4.0 CONCLUSIONS AND RECOMMENDATIONS

- Increasing the elastic modulus of the resin in a wet lay-up may increase the load capacity of FRP-strengthened, concrete beams. However, this enhancement decreases as the failure mode changes from flexural failure to less desirable failure modes.
- Because fatigue performance is dependent on load capacity, the resin effect may also increase the fatigue response of FRP-strengthened beams.
- The elastic modulus of the resin has no effect on the stiffness of beams.
- To verify and quantify the relationship between elastic modulus of the resin and performance, further testing would need to be conducted on full-size beams with realistic design configurations.

## 5.0 REFERENCES

American Society for Testing and Materials (ASTM) Subcommittee C09.61. 2001. *Standard Test Method for Flexural Strength of Concrete (Using Simple Beam with Third-Point Loading)*. Designation ASTM C 78-00. West Conshohocken, PA.

Seamanontapriya, Dharadon. 2001 (in press). *Behavior of FRP Composite-Strengthened Beams under Static and Cyclic Loading*. Masters project report, Department of Civil, Construction, and Environmental Engineering, Oregon State University.



THE FIBERWRAP® COMPANY™

## Tyfo® SEH-51 Composite using Tyfo® S Epoxy

### DESCRIPTION

The Tyfo® SEH-51 Composite is an ICBO ER-5282 listed material comprised of Tyfo® S Epoxy and Tyfo® SEH-51 reinforcing fabric. Tyfo® SEH-51 is a custom weave, uni-directional glass and aramid hybrid fabric used in the Tyfo® Fiberwrap System. The glass material is oriented in the 0° direction with aramid fibers at 90°. The Tyfo® S Epoxy is a two-component epoxy resin material for bonding applications.

### USE

Tyfo® SEH-51 Fabric is combined with Tyfo® epoxy material to add strength and ductility to bridges, buildings, and other structures.

### ADVANTAGES

- ICBO ER-5282 listed material
- Good high & low temperature properties
- Long working time
- High elongation
- Ambient cure
- 100% solvent-free
- Rolls can be cut to desired widths prior to shipping

### COVERAGE

Approximately 575 sq ft surface area with 3 to 4 units of Tyfo® S Epoxy and 1 roll of Tyfo® SEH-51 Fabric when used with the Tyfo® Satorator.

### PACKAGING

Order Tyfo® S Epoxy in 55-gallon (208L) drums or pre-measured units in 5-gallon (19L) containers. Order Tyfo® SEH-51 Fabric in 54" x 150' lineal feet (1.4m x 45.7m) rolls. Typically ships in 12" x 12" x 64" (305mm x 305mm x 1626mm) boxes.

### EPOXY MIX RATIO

100:0 component A to 42:0 component B by volume (100 component A to 34.5 component B by weight)

### SHELF LIFE

Epoxy - two years in original, unopened and properly stored containers.  
Fabric - ten years in proper storage conditions.

### STORAGE CONDITIONS

Store at 40° to 60° F (4° to 32° C). Avoid freezing. Store rolls flat, not on ends, at temperatures below 100° F (30° C). Avoid moisture and water contamination.

### CERTIFICATE OF COMPLIANCE

- Will be supplied upon request, complete with state and federal packaging laws with copy of labels used.
- Material safety data sheets will be supplied upon request.
- Possesses 0% VOC level

002 Tyfo® SEH-51

### TYPICAL DRY FIBER PROPERTIES

|                     |   |
|---------------------|---|
| Tensile Strength    | 470,000 psi (3.24 GPa)                                |
| Tensile Modulus     | 10.5 x 10 <sup>6</sup> psi (72.4 GPa)                 |
| Ultimate Elongation | 4.5%  |
| Density             | 0.022 lbs./in. <sup>3</sup> (2.58 g/cm <sup>3</sup> ) |
| Weight per sq. yd.  | 27 oz. (915 g/m <sup>2</sup> )                        |
| Fiber Thickness     | 0.014 in. (0.36mm)                                    |

### COMPOSITE GROSS LAMINATE PROPERTIES

| PROPERTY   | ASTM METHOD | TYPICAL TEST VALUE                          | DESIGN VALUE*                              |
|--|-------------|---|--|
| Ultimate tensile strength in primary fiber direction, psi  | D-3039      | 63,400 psi (578 MPa)<br>(4.17 kN/in. width) | 65,720 psi (460 MPa)<br>(3.3 kN/in. width) |
| Elongation at break  | D-3039      | 2.2%  | 2.2%                                       |
| Tensile Modulus, psi                                       | D-3039      | 1.76 x 10 <sup>6</sup> psi (20.1 GPa)       | 3.03 x 10 <sup>6</sup> psi (20.9 GPa)      |
| Ultimate tensile strength 90 degrees to primary fiber, psi | D-3039      | 6,250 psi (43 MPa)                          | 6,000 psi (41.4 MPa)                       |
| Laminate Thickness   |             | 0.05 in. (1.3 mm)                           | 0.05 in. (1.3mm)                           |

\* Design and specification values will vary based on individual project requirements and applicable safety factors. Consult Tyfo Co. LLC engineers to determine appropriate design values.

### EPOXY MATERIAL PROPERTIES

| Curing Schedule 72 hours post cure at 140° F (60° C). |                      |                           |
|---|----------------------|---------------------------|
| PROPERTY  | ASTM METHOD          | TYPICAL TEST VALUE*       |
| T <sub>g</sub> 140° F (60° C)<br>Post Cure (24 hours) | ASTM D-4065          | 180° F (82° C)            |
| Tensile Strength <sup>1</sup> , psi                   | ASTM D-833<br>Type 1 | 10,500 psi<br>(72.4 MPa)  |
| Tensile Modulus, psi                                  | ASTM D-638<br>Type 1 | 491,000 psi<br>(3.18 GPa) |
| Elongation Percent                                    | ASTM D-638<br>Type 1 | 5.0%                      |
| Flexural Strength, psi                                | ASTM D-790           | 17,900 psi<br>(123.4 MPa) |
| Flexural Modulus, psi                                 | ASTM D-790           | 452,000 psi<br>(3.12 GPa) |

<sup>1</sup> Testing temperature: 70° F (21° C) Crosshead speed: 0.5 in./minute. Crosshead: 2716-0355 - 20 kN  
\* Specimen values can be created upon request.



TABLE 2.1 Typical Properties of Commercial Reinforcing Fibers

18

| Fiber              | Typical diameter ( $\mu\text{m}$ ) <sup>a</sup> | Specific gravity | Tensile modulus, GPa (10 <sup>6</sup> psi) | Tensile strength, GPa (10 <sup>3</sup> psi) | Strain to failure (%) | Coefficient of thermal expansion (10 <sup>-6</sup> m/m per °C, 0-100°C) <sup>b</sup> | Poisson's ratio |
|--------------------|---|------------------|--|---|-----------------------|--|-----------------|
| Glass              |   |                  |  |   |                       |  |                 |
| E glass            | 10 (round)                                      | 2.54             | 72.4 (10.5)                                | 3.45 (500)                                  | 4.8                   | 5  | 0.2             |
| S glass            | 10 (round)                                      | 2.49             | 86.9 (12.6)                                | 4.30 (625)                                  | 5.0                   | 2.9  | 0.22            |
| PAN-carbon         |   |                  |  |   |                       |  |                 |
| T-300 <sup>c</sup> | 7 (round)                                       | 1.76             | 228 (33.5)                                 | 3.2 (470)                                   | 1.4                   | -0.1 to -0.5 (longitudinal)<br>7-12 (radial)   | ~0.2            |
| AS <sup>d</sup>    | 7 (round)                                       | 1.77             | 220 (32)                                   | 3.1 (450)                                   | 1.2                   | -0.5 to -1.2 (longitudinal)<br>7-12 (radial)   |                 |
| T-40 <sup>c</sup>  | 6 (round)                                       | 1.81             | 276 (40)                                   | 5.65 (820)                                  | 2                     |  |                 |
| HMS <sup>d</sup>   | 7 (round)                                       | 1.85             | 344.5 (50)                                 | 2.34 (340)                                  | 0.58                  |  |                 |
| GY-70 <sup>e</sup> | 8.4 (bilobal)                                   | 1.96             | 483 (70)                                   | 1.52 (220)                                  | 0.38                  |  |                 |

2 MATERIALS

|                                |              |      |            |            |      |                                   |      |
|--------------------------------|--------------|------|------------|------------|------|-----------------------------------|------|
| Pitch-carbon                   |              |      |            |            |      |                                   |      |
| P-55 <sup>c</sup>              | 10           | 2.0  | 380 (55)   | 1.90 (275) | 0.5  | -0.9 (longitudinal)               |      |
| P-100 <sup>c</sup>             | 10           | 2.15 | 690 (100)  | 2.2 (325)  | 0.31 | -1.6 (longitudinal)               |      |
| Kevlar 49 <sup>f</sup>         | 11.9 (round) | 1.45 | 131 (19)   | 3.62 (525) | 2.8  | -2 (longitudinal)<br>+59 (radial) | 0.35 |
| Boron                          | 140 (round)  | 2.7  | 393 (57)   | 3.1 (450)  | 0.79 | 5                                 | 0.2  |
| SiC                            | 133 (round)  | 3.08 | 400 (58)   | 3.44 (485) | 0.84 | 1.5                               | —    |
| Al <sub>2</sub> O <sub>3</sub> | 20 (round)   | 3.95 | 379.3 (55) | 1.90 (275) | 0.4  | 8.3                               |      |

FIBERS

<sup>a</sup>1  $\mu\text{m}$  = 0.000039 in.<sup>b</sup>1 m/m per °C = 0.556 in./in. per °F.<sup>c</sup>Amoco.<sup>d</sup>Hercules Inc.<sup>e</sup>Celanese.<sup>f</sup>DuPont.

CEMENT OR SI WAX  
ENT SPECIMEN

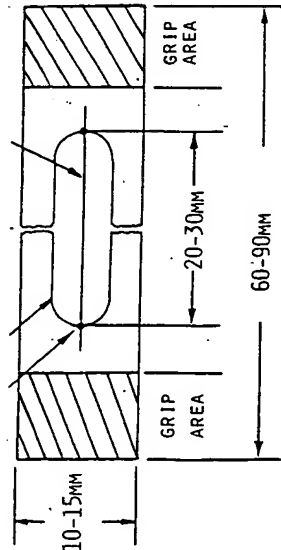


FIG. 2.2 Mounting tab for single filament testing (ASTM D3379-75).

Grips of a tension testing machine, its midsection is either cut or burnt away. The tension test is carried out at a constant loading rate until the filament fractures. From the load-time record of the test, the following tensile properties are determined:

$$\text{Tensile strength } \sigma_{fu} = \frac{F_u}{A_f} \quad (2.1)$$

and

$$\text{Tensile modulus } E_f = \frac{L_f}{CA_f} \quad (2.2)$$

where:  $F_u$  = force at failure

$A_f$  = average cross-sectional area, measured by a planimeter from the photomicrographs of filament ends

$L_f$  = gage length

$C$  = true compliance, determined from the chart speed, loading rate, and the system compliance

Similar tests can also be performed to measure tensile properties of fiber strands (either dry or resin impregnated). Generally, the average tensile strength and modulus of fiber strands are lower than those measured on single filaments.

Tensile stress-strain diagrams for all reinforcing fibers in use are linear up to the point of failure, as shown in Fig. 2.3. They also exhibit very low strains to failure and a brittle failure mode. Although the absence of yielding does not reduce the load-carrying capacity of the fibers, it does make them prone to damage in handling as well as during contact with other surfaces. In continuous manufacturing operations, such as filament winding, frequent fiber breakage resulting from such damages may slow the rate of production.

The high tensile strengths of the reinforcing fibers are generally attributed to their filamentary form in which there are statistically fewer number

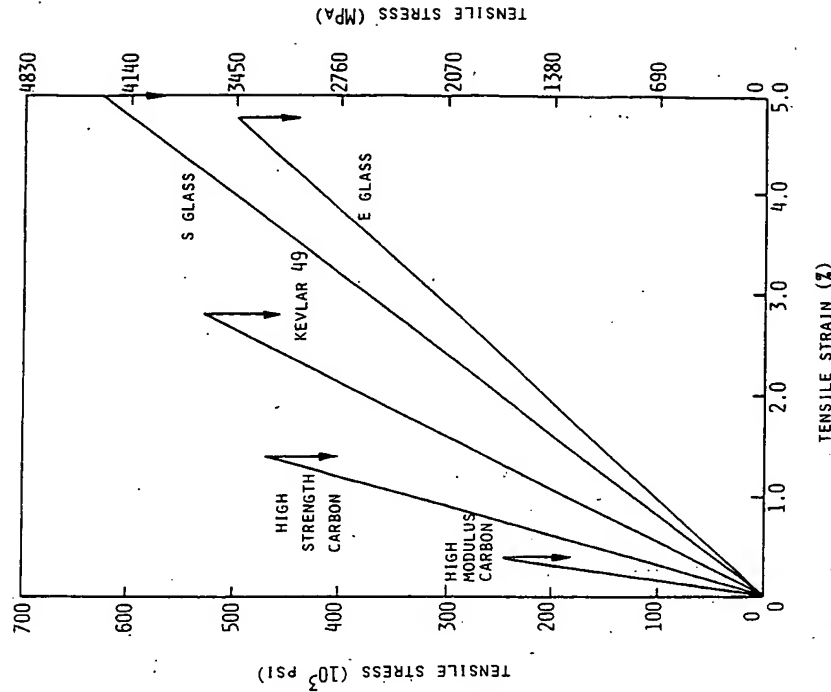


FIG. 2.3 Tensile stress-strain diagrams for various reinforcing fibers.

Table 2.4 Advantages and Disadvantages of Reinforcing Fibers

| Fiber                              | Advantages                                  | Disadvantages   |
|------------------------------------|---|---|
| E-glass, S-glass                   | High strength<br>Low cost                   | Low stiffness<br>Short fatigue life<br>High temperature sensitivity |
| Aramid (Kevlar)                    | High tensile strength<br>Low density        | Low compressive strength<br>High moisture absorption                |
| Boron                              | High stiffness<br>High compressive strength | High cost   |
| Carbon (AS4, T300, C6000)          | High strength<br>High stiffness             | Moderately high cost  |
| Graphite (GY-70, pitch)            | Very high stiffness                         | Low strength<br>High cost   |
| Ceramic (silicon carbide, alumina) | High stiffness<br>High use temperature      | Low strength<br>High cost   |

Table 2.5 Fiber Properties

| Type              | Manufacturer  | Tensile strength<br>MPa (ksi) | Modulus<br>GPa (Msi) | Density<br>(g/cm <sup>3</sup> ) |
|-------------------|---------------|-------------------------------|----------------------|---------------------------------|
| E-glass           | Corning       | 3,450 (500)                   | 72.5 (10.5)          | 2.54                            |
| S-glass           | Corning       | 4,480 (650)                   | 85.6 (12.4)          | 2.49                            |
| Carbon            |               |                               |                      |                                 |
| AS4               | Hercules      | 3,730 (540)                   | 235 (34)             | 1.81                            |
| T300              | Union Carbide | 2,760-3,450<br>(400-500)      | 228 (33)             | 1.76                            |
| HTS               | Hercules      | 2,830 (410)                   | 248 (36)             | 1.82                            |
| IM-6              | Hercules      | 4,480 (650)                   | 290 (42)             | 1.80                            |
| IM-7              | Hercules      | 5,170 (750)                   | 290 (42)             | 1.80                            |
| Graphite          |               |                               |                      |                                 |
| T-50              | Union Carbide | 2,070 (300)                   | 393 (57)             | 1.67                            |
| GY-70             | Celanese      | 1,725 (250)                   | 517 (75)             | 1.86                            |
| Pitch, type P     | Union Carbide | 1,725 (250)                   | 345 (50)             | 2.02                            |
| Boron             | AVCO          | 3,280-3,660<br>(475-530)      | 365-414<br>(53-60)   | 2.1-3.0                         |
| Kevlar (aramid)   | DuPont        | 3,800 (550)                   | 131 (19)             | 1.45                            |
| Silicon carbide   |               |                               |                      |                                 |
| 5.6 mil/C (SCS-2) | Tektren       | 4,140 (600)                   | 400 (58)             | 3.05                            |
| Nicalon           | Nippon Carbon | 2,070 (300)                   | 172 (25)             | 2.60                            |
| Alumina           |               |                               |                      |                                 |
| FP-2              | Dupont        | 1,725 (250)                   | 380 (55)             | 3.70                            |
| Nexel 610         | 3M            | 1,900 (275)                   | 370 (54)             | 3.75                            |
| Saphikon          | Saphikon      | 3,100 (450)                   | 380 (55)             | 3.80                            |
| Silica            | —             | 5,800 (840)                   | 72.5 (10.5)          | 2.19                            |
| Tungsten          | —             | 4,140 (600)                   | 414 (60)             | 19.3                            |

composite and high moisture absorption. Boron fibers, not widely used at present, are useful in local stiffening applications because of their high stiffness.

Carbon (graphite) fibers come in many types with a range of stiffnesses and strengths, depending on the processing temperatures. High strength and high stiffness carbon fibers (AS4, T300, C6000), are processed at temperatures between 1200° and 1500°C (2200° and 2700°F). Ultrahigh stiffness graphite fibers (GY-70, Pitch) are processed at temperatures between 2000° and 3000°C (3600° and 5400°F). The increase in stiffness is achieved at the expense of strength, as shown in Table 2.5. Ceramic fibers such as silicon carbide and aluminum oxide have high stiffness and moderate strength and are used in metal-matrix and ceramic-matrix composites for high temperature applications.

Most fibers behave linearly to failure, as shown in Figure 2.8. Carbon fibers, such as the AS4 fiber, however, display a nonlinear stiffening effect. One important property of the fiber related to strength and stiffness is the ultimate strain or strain to failure, because it influences greatly the strength of the composite laminate.

As mentioned previously, the basis of the superior performance of composites lies in the high specific strength (strength to density ratio) and high specific stiffness (modulus to density ratio). These two properties are controlled by the fibers. A two-dimensional comparative representation of some typical fibers from the point of view of specific strength and specific modulus is shown in Figure 2.9.

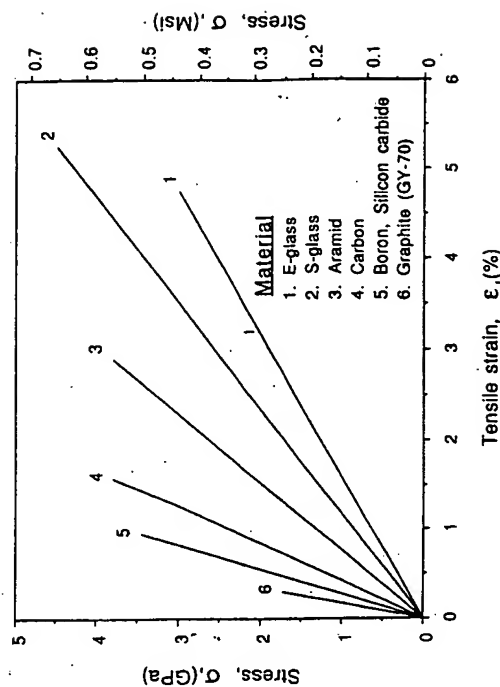


Fig. 2.8 Stress-strain curves of typical reinforcing fibers.



THE FIBRWRAP® COMPANY

## Tyfo® SEH-51 Composite using Tyfo® S Epoxy

### DESCRIPTION

The Tyfo® SEH-51 Composite is an ICCO ER-6282 listed material comprised of Tyfo® S Epoxy and Tyfo® SEH-51 reinforcing fabric. Tyfo® SEH-51 is a custom woven, uni-directional glass and aramid hybrid fabric used in the Tyfo® Formwrap System. The glass material is oriented in the 0° direction with aramid fibers at 90°. The Tyfo® S Epoxy is a two-component epoxy matrix material for bonding applications.

### USE

Tyfo® SEH-51 Fabric is combined with Tyfo® epoxy material to add strength and durability to bridges, buildings, and other structures.

### ADVANTAGES

- ICCO ER-6282 listed material
- Good high & low temperature properties
- Long working time
- High elongation
- Ambient cure
- 100% solvent-free
- Rolls can be cut to desired widths prior to shipping

### COVERAGE

Approximately 67.5 sq. ft. surface area with 330-lb. rolls of Tyfo® S Epoxy and 1 roll of Tyfo® SEH-51 Fabric when used with the Tyfo® S Epoxy.

### PACKAGING

Order Tyfo® S Epoxy in 55-gallon (208L) drums or pre-measured units in 3-gallon (11.3L) containers. Order Tyfo® SEH-51 Fabric in 54" x 150' (16.8m x 45.7m) rolls. Typically ships in 12" x 12" x 64" (305mm x 305mm x 1626mm) boxes.

### EPOXY MIX RATIO

100.0 component A to 42.0 component B by volume (100 component A to 34.5 component B by weight)

### SHELF LIFE

Epoxy - two years in original, unopened and properly stored containers.  
Fabric - ten years in proper storage conditions.

### STORAGE CONDITIONS

Store at 40° to 90° F (4° to 32° C). Avoid freezing. Store rolls flat, not on ends, at temperatures below 100° F (30° C). Avoid moisture and water contamination.

### CERTIFICATE OF COMPLIANCE

- Will be supplied upon request, complete with state and federal packaging laws with copy of labels used.
  - Material safety data sheets will be supplied upon request.
  - Processes 6% VOC level
- ©2011 FYFE LLC

### TYPICAL FIBER PROPERTIES

|                     |  |
|---------------------|--|
| Tensile Strength    | 470,000 psi (3.24 GPa)                               |
| Tensile Modulus     | 18.5 x 10 <sup>6</sup> psi (12.8 GPa)                |
| Ultimate Elongation | 4.5%   |
| Density             | 0.002 lb./in. <sup>3</sup> (2.50 g/cm <sup>3</sup> ) |
| Weight per sq. yd.  | 27 oz. (919 g/m <sup>2</sup> )                       |
| Fiber Thickness     | 0.014 in. (0.35mm)                                   |

### COMPOSITE GROSS LAMINATE PROPERTIES

| PROPERTY   | ASTM METHOD | TYPICAL TEST VALUE                       | DESIGN VALUE*                           |
|--|-------------|--|---|
| Ultimate tensile strength in primary fiber direction, psi  | D-3039      | 63,000 psi (575 MPa)<br>(4.17 MPa width) | 63,750 psi (580 MPa)<br>(5.3 MPa width) |
| Elongation at break  | D-3039      | 2.2%                                     | 2.2%                                    |
| Tensile Modulus, psi                                       | D-3039      | 2.79 x 10 <sup>6</sup> psi (23.1 GPa)    | 3.00 x 10 <sup>6</sup> psi (20.8 GPa)   |
| Ultimate tensile strength 90 degrees to primary fiber, psi | D-3039      | 6,250 psi (43 MPa)                       | 6,000 psi (41.4 MPa)                    |
| Laminate Thickness   |             | 0.03 in. (1.3 mm)                        | 0.03 in. (1.3 mm)                       |

\* Design and specification values will vary based on individual project requirements and applicable safety factors. Consult with FYFE Co. LLC engineers to determine appropriate specification values.

### TYPICAL MATERIAL PROPERTIES

| Curing Schedule 72 hours post cure at 160° F (50° C). |                      |                           |
|---|----------------------|---------------------------|
| PROPERTY  | ASTM METHOD          | TYPICAL TEST VALUE*       |
| Tg 160° F (50° C)<br>Post Cure (24 hours)             | ASTM D-4068          | 160° F (50° C)            |
| Tensile Strength <sup>1</sup> , psi                   | ASTM D-638<br>Type 1 | 10,500 psi<br>(72.4 MPa)  |
| Tensile Modulus, psi                                  | ASTM D-638<br>Type 1 | 491,000 psi<br>(3.18 GPa) |
| Elongation Percent                                    | ASTM D-638<br>Type 1 | 5.0%                      |
| Flexural Strength, psi                                | ASTM D-720           | 17,000 psi<br>(121.4 MPa) |
| Flexural Modulus, psi                                 | ASTM D-720           | 432,000 psi<br>(3.12 GPa) |

<sup>1</sup> Testing temperature: 70° F (21° C). Crosshead speed: 0.5 in. (12.5mm). Crosshairs 270-005-00 mm.  
\* Specimen thickness can be checked upon request.

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